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Potential of impulse drying technology for molded pulp products manufacture

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ABSTRACT

The vision of the Green Fiber Bottle (GFB) project is to develop a paper bottle for beer, which will be both recyclable and biodegradable. The early prototypes of the bottle are very promising but there are huge technical and scientific challenges ahead to mature the production technology. The possibility of applying the concept of impulse drying during the drying stage is suggested. This would give benefits in terms of productivity and it would also reduce energy consumption.

With the aim of understanding and controlling the impulse drying phenomena, a simplified approach is proposed. Finally, a potential design for a testing equipment is described.

1. INTRODUCTION

The vision of the Green Fiber Bottle (GFB) project is to develop a paper bottle for beer, which will be both recyclable and biodegradable (Figure 1). The bottle is made out of paper pulp, which is a renewable resource. In order to enhance the green image of the product, the production technology has to offer the possibility of high-level energy saving.



Figure 1: The Green Fiber Bottle project main features and research partners

The manufacturing process involved in the production of the early prototypes of the GFB resembles the one used in the production of the thermoformed type of product. However, to enable the mass production of the product, technological improvements have to be introduced in order to achieve certain requirements, such as an appropriate throughput and low energy consumption.

Molded pulp products are made from cellulose fibers dispersed in water then formed, drained and dried. Like in the conventional papermaking process, the most energy intensive operation (also in terms of time) is drying.

It is in this process stage that an innovative way of drying the products based on the concept of impulse drying can be exploited.

The goal of this paper is to propose a simplified approach to understand and control the impulse drying effect thus allowing its application in the manufacturing of molded pulp products.

This paper provides first an introduction of the main features of impulse drying. Section 3 discusses the applicability of this technology in the manufacturing of molded pulp products and a simplified approach to it is presented in Section 4. A design for a testing equipment to verify the suggested theory is finally described in Section 5.

It is the vision that the Green Fiber Bottle could be adopted for packaging drinks of various nature with the very ambitious goal “to bottle beer in a paper bottle”, which is highly relevant for the Danish industrial sector, and could have the potential of a global impact as well.

2. IMPULSE DRYING

Impulse drying is a process in which water is removed from a wet paper web by the combination of applied pressure and intense heat. It was introduced in the beginning of the 1980s by Wahren [1] and it attracted considerable interest from the paper industry as a means of reducing energy consumption in the drying process.

In this process, the wet web is exposed to pressures ranging from 10 to 80 bar and to hot surface temperatures typically between 100 – 350°C. The dwell or nip residence time is around 20 to 50 ms (this is why “impulse”) and it takes place in a so-called shoe-nip press, that replaces the conventional press nip [2].

Impulse drying is similar in nature to conventional wet-pressing operations but with the application of heat. The applied heat has two main roles: it reduces the viscous resistance of the water and it softens the structure of the paper pulp, so that it becomes more compressible. It was also suggested that if the heat transfer rate is sufficiently high, a vapor phase can be generated on the wet paper side in contact with the high temperature medium [3]. This may assist in the dewatering process as the expanding steam can displace the bound water. This effect was recently studied and termed *flashing-assisted displacement dewatering* by Lucisano et al. [4].

Pilot scale experiments showed that some of the water present in the paper evaporates, and that some of it leaves the sheet in liquid form [5]. This means that less heat than what would be actually needed to evaporates all the water content has to be transferred resulting in a faster and a less energy consuming process [6].

Understanding the mechanism of steam forming and its motion through a fibrous and porous medium such as paper pulp is difficult. The phenomena was simplified and related to a class of heat transfer problems known as Stefan problems [7] but an exact interpretation, sustained by experimental evidences, has not been given yet.

The introduction of the impulse drying technology in the paper industry has been also hampered by several operational problems. One such problem is delamination, which is defined as a sudden reduction of the strength in the thickness direction of the paper web. To prevent delamination, the fiber-to-fiber bonds must withstand the energy generated by the water, gases or steam moving in any direction during the impulse drying process [8]. A way to inhibit delamination consists of maintaining the pressure after opening the shoe-nip, allowing the paper to cool gradually down and avoiding the outburst of the steam trapped inside. This results in a longer process time and increased investment in equipment. Re-wetting of the paper as it leaves the drying unit could also occur if the water is not effectively removed.

3. IMPULSE DRYING FOR THERMOFORMED MOLDED PULP PRODUCTS MANUFACTURE

In the production of the molded pulp products falling into the category of the thermoformed type, processing condition are mainly characterized by the molding temperature, the pressure and the process time [9]. As explained in the previous paragraph, these are also the three main variables on which the impulse drying technology is based.

The process and the technologies involved can thus be tailored and improved in order to meet the requirements needed to develop the *flashing-assisted displacement dewatering effect*, which are a sufficiently high and controlled temperature and pressure. The operational problems that the impulse drying technology has encountered can be controlled and overcome. One such problem is the contact time between the impulse drying unit and the paper, required to control the energy transfer. In the manufacturing of molded pulp products there are not specific time constraints, unless the achievement of a certain throughput in a mass production scenario. To avoid delamination, the part can be kept inside the mold as long as the gases or steams trapped inside have been completely removed.

The technology can be applied in the production of any open geometry of molded pulp products and, with the correct setup, can be extended to the production of products with a three-dimensional closed geometry.

Regarding the production of a bottle shaped molded pulp product, ecoXpac has recently deposited a patent [10]. The technology has proven to work for the production of prototypes but it does not exploit any impulse drying effect, that would give benefits in terms of energy saving as well as reduction in process time.

4. IMPULSE DRYING: HEAT CONDUCTION AND VAPOR-WATER DIFFUSION

With the aim of understanding and controlling the impulse drying phenomena, a simplified approach is proposed. The idea is to describe the problem by looking at the thermodynamic state of the water content inside the paper.

The thermodynamic state of the system at a specific time is fully defined by knowing the values of the state variables, in this case pressure and temperature. Some further assumptions have to be made regarding the thermodynamic equilibrium of the specific process stage considered.

The approach suggested refers to a conventional thermoforming process in which the pre-formed wet molded part is placed inside a mold. Assuming that temperature and pressure of the considered domain (i.e. the molded pulp part) can be controlled at each instant of time, two main process steps are identified:

1. Once the system is pressurized, the heat conducts from the heating element inside the wet paper part until a certain thickness of it reaches a definite temperature. At each instant of time, thermal and mechanical equilibrium is assumed.
2. Pressure is then released from one side of the system only and the water content in the top layers of the paper part flashes into vapor. The expanding steam diffuses along the paper thickness in the direction of the pressure gradient and it displaces the remaining liquid water. In this stage, a phase equilibrium is assumed, since only the diffusion of the vapor layer is taken into account.

The process can thus be summarized in a heat conduction stage followed by a vapor-water diffusion stage.

The duration of step one can be estimated by running a numerical simulation of the heat transfer process along the thickness direction of the paper part. The rate equation that appropriate quantifies the heat conduction is known as Fourier's law [11]. For the one-dimensional case is as follow:

$$q_x'' = -k \frac{dT}{dx} \quad (1)$$

The heat flux q_x'' [W/m²] is the heat transfer rate in the x-direction, in this case the thickness direction of the paper part, per unit area perpendicular to the direction of transfer, and it is proportional to the temperature gradient, dT/dx. The minus sign is a consequence of the fact that heat is transferred in the direction of decreasing temperature.

In the second step, the diffusive mechanism that can be considered is known as Stephan diffusion [12], which is also the dominating vapor transport mechanism in conventional paper drying. The driving force for Stephan diffusion is the gradient in the partial pressure of vapor:

$$\frac{\dot{m}_v}{A} = \varepsilon \Psi \frac{D_v}{R_v T} \frac{p_{tot}}{p_{tot} - p_v} \frac{dp_v}{dx} \quad (2)$$

Where: ε void fraction of gas filled pores

Ψ labyrinth factor describing tortuosity of the flow path

D_v diffusivity of water vapor in air

R_v gas constant of water vapor (461,5 J/kg water/K)

p_v partial pressure of vapor

A major disadvantage of the Stefan theory is that the diffusion coefficients are not tabulated. For sake of simplicity, one can also refer to Fick's second law of diffusion that can predict how diffusion causes the concentration to change with time.

5. DESIGN FOR TESTING THE IMPULSE DRYING EFFECT

In order to verify the impulse drying effect in the production of molded pulp products, a possible testing device is described. As highlighted in the previous section, the impulse drying phenomena can be divided into a heat conduction and a vapor-water diffusion stage. The device has to pressurize the paper part before the heat is applied, thus avoiding any water content to turn into vapor before the first stage is finished.

In Figure 2 a schematic design for a testing device is illustrated. The main idea is to compress a certain volume of air that is above the paper part. The same pressing element is then used to heat up the paper part. Previous calculations have shown that (assuming an isentropic process) by compressing a volume of 0,02 m³ of air a pressure of about 25 bar can be reached.

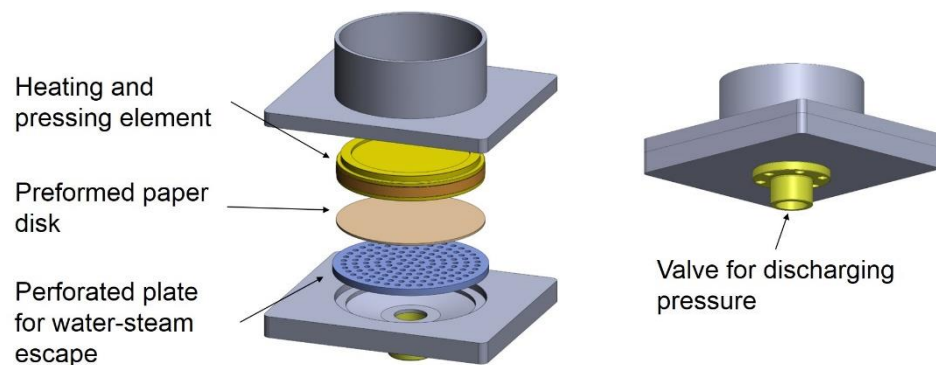


Figure 2: System configuration for impulse drying testing for molded pulp products manufacture. Courtesy of EcoXpac

The second stage starts by releasing the pressure from the part of the mold: a simple valve can be suitable. In this way, a pressure drops from 25 bar to ambient pressure can be realized. This should be sufficient to drive the diffusion of the vapor phase along the paper thickness, according to the Stefan diffusion. Moreover, while in the conventional thermoforming process the vacuum is applied, here can be avoided thus reducing the related energy consumption.

6. CONCLUSIONS

- Main features of the impulse drying phenomena have been described, especially how the moving vapor layer can assist in the dewatering process by displacing the bound water.
- The applicability of the impulse technology during the drying phase of thermoformed products has been proposed. The packaging industry would benefit from such an improvement from a productivity point of view and it would also reduce energy consumption.
- A simplified approach of the impulse drying effect has been proposed by considering two main process steps: heat conduction and vapor-water diffusion.
- Finally, a design for a testing equipment has been described and it has to be implemented in order to experimentally verify the proposed theory.

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